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Technical Memorandum No. 33-95

Masers

[W M Higin]

JET PROPULSION LABORATORY  
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PASADENA, CALIFORNIA

May 26, 1962

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## II. DISCUSSION OF INDUCED EMISSION BY ATOMS

### ABSTRACT

The following discussion of lasers is intended primarily for the electronics engineer interested in a quick introduction to the subject. After a concise review of the physics of induced radiative emission by atoms, a fairly complete discussion of the use of atoms as circuit elements is given. The concluding sections describe the actual application of masers to sensitive receiving systems.

### 1. INTRODUCTION

It is common observation that technological progress is becoming faster and faster. The time interval between the discovery of a physical phenomenon and the actual engineering application of the principle involved is often lengthened due to the development of higher frequencies. I. S. C. and N. L. Lands, for low noise receiving systems

This paper deals exclusively with masers for low noise receiving systems. In conventional electron tubes the amplification quality is limited because the "hot electrons" give rise to thermal noise. This noise, however, has its origin in the particular nature of electrons, i.e., due to the discreteness of electronic charge. The noise, on the other hand, depends on induced emission of radiation from atoms for its amplification properties and is significantly greater than any electron tube or semiconductor device.

1954 Antennas designed at Columbia University versus Ref. 1

1956 Solid-state laser-helium theory developed at Harvard University, Ref. 2

1957 Solid-state masers operated at Bell Telephone Laboratories, Ref. 3 and MIT, Ref. 4

1958 Rabi discovered maser material at University of Michigan, Ref. 5; tracking wave maser operated at Bell, Ref. 6.

1960 Rabi solid-state maser operated at Hughes Research Laboratories, Ref. 7.

It is to be noted that the development of microwave masers occurred in the short interval 1955-1960. Since 1961 the overwhelming proportion of research and

### II. DISCUSSION OF INDUCED EMISSION BY ATOMS

The mechanism by which atoms can radiate discrete amounts of energy is called induced emission. An atom makes a transition from one energy state to another and gives up a quantum of energy which is given by

$$\hbar \cdot F = I$$

where

$\hbar$  Planck constant

$F$  frequency of radiation

$I$  energy of 1 level. For convenience, the second order of numbers for higher energy levels shall be used.

Feedback, Ref. 8, on quantum theory usually describes a classical analog of induced emission in terms of a mechanically oscillating charge. If the oscillating charge is in proper phase relative to the electric field of the incident radiation, then energy is transferred from the quantum system to such a charge. In addition to phase synchronization, the classical model is not quite as versatile.

It has occurred to the author that there exists a better classical model with which electrical engineers are more familiar, the induction generator. It should be recalled that if the source of radio waves from an induction machine is rotating at angular speed greater than the synchronous speed, then power will be delivered to the load. The foregoing observation is made that the non-harmonically oscillating device is able to deliver power to the lines if

and conversely

If it is noted that several of absolute zero temperature the induction field has a nonresonant part, called the permanent current. The induced emission due to the permanent radiation field is referred to as spontaneous emission and is seen to become important at higher frequencies. Vertically, the situation is a little more complex than it was

It is to be noted that the field due to such a current is also in the same direction as a permanent magnet. Indeed, the permanent field can be shown to have all the properties of a permanent magnet except that it is finite. See also Ref. 9, Ref. 10.

where

$\omega$  angular speed of rotating field due to wave currents

2

atoms and has been discussed earlier by Siegan (Ref. 4).

In general atoms and molecules will interact with a radiation field either as electric dipoles, ammonia molecules as dipole-dipole dipoles, or as atoms.

The analytical procedure used to account for the interaction between atoms and an electromagnetic field is the same as for lossless dielectrics. This requires the introduction of complex susceptibility, magnetoelectric, and Maxwell's equations. Thus let

$$\mathbf{g} = \mathbf{H} - \mathbf{H}_0 \quad (1)$$

where

$\mathbf{H}$  = magnetic flux density

$\mathbf{H}_0$  = permeability of medium

$\mu_0$  = permeability of free space

$H$  = field strength

$\chi$  = magnetic susceptibility

The presence of a loss mechanism in the medium has the effect of introducing a phase shift between  $\mathbf{g}$  and  $\mathbf{H}$ . Hence, the initial practice is to set

$\mathbf{g} = \mathbf{g}' + \mathbf{g}''$

where

$\mathbf{g}'$  = real part of susceptibility

$\mathbf{g}''$  = imaginary part of  $\mathbf{g}$  due to losses

For convenience of derivation and to conform to notation more common in dielectrics one finds very often

## M. ATOMS AS CIRCUIT ELEMENTS

It now remains to derive an expression for the power dissipated in the lossy medium. The real part of the product of voltage, proportional to  $\mathbf{g}$ , and current (proportional to  $\mathbf{H}$ ) leads to the desired result

$$P = \mathbf{g} \cdot \mathbf{H} - \mathbf{g}'' \cdot \mathbf{H} \quad (2)$$

where

( $\mathbf{g}$  = complex conjugate of quantity in parenthesis)

constant dependence on geometrical configuration

Alternatively the power absorbed by the medium can be calculated from atomic physics. This is given by the product of the  $k$ , the energy per transition,  $n$ , the number of atoms available, and  $p$ , the probability for the transition. Thus,

$$P = k n p \quad (3)$$

where

$k$  = constant of proportionality

Hence, from Eqs. (2) and (3)

$$P = k n p / \mathbf{H} \quad (4)$$

It is to be noted that the transition probability  $p$  is calculated by quantum mechanical rules and is determined by such parameters as the properties of the atom, such as its mass, and the environment for these atoms, and geometrical dimensions of the medium subject to the electromagnetic field (particularly for dielectric paramagnetic crystals).

The expression given in Eq. (4) can be worked out for each situation or configuration. However, the expression more

general is that if  $n_0 > n$ , then it is possible for the absorbed power to become negative. This means that power will be delivered by the atoms in the field. The fact that  $k > 0$  is referred to as population inversion and can be achieved in different ways.

Independent of the mechanism by which inversion occurs there are observed many variations on what Eq. (4) generally is for these situations. A few of the more important ones will be derived here. The calculations are straightforward, but certain conventions and notations which have been used lead to obscure the logical development.

### B. Input Impedance of a Cavity Filled with Active Material

In practice only a single mode out of many is of importance, the resonant cavity then is represented by a parallel resonant circuit tuned to the same frequency. The current in the circuit of Fig. 1 is given by

$$I = C \frac{dV}{dt} - \frac{1}{jZ} \frac{dV}{dt} \quad (5)$$

where  $Z$  is the resistance due to the active material. (Resistance is also introduced but will be neglected here.) For the steady state sinusoidal case, let

$$I = I_0 e^{j\omega t} \quad (6)$$

where  $I_0$  is the amplitude of the current.

Substituting into Eq. (5) gives

$$I_0 = V \frac{C}{jZ} \quad (7)$$

where  $I$  and  $V$  are complex numbers. Then the input impedance is given by

$$Z = \frac{V}{I_0} \quad (8)$$

Finally  $Z$  will be much larger than both  $C$  and  $Q_0$ .

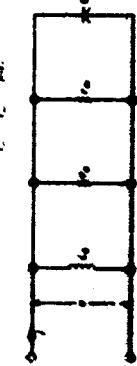
However,

$$Z = \frac{V}{I_0} = \frac{V}{C \frac{dV}{dt}} = \frac{1}{C \frac{d}{dt} \left( \frac{V}{V} \right)} \quad (9)$$

It is seen from Eq. (9) that  $Z$  can be larger than unity if  $V$  is negative. If  $V > 1$ , then the magnitude of  $Z$  is larger than the incident voltage and transmission is blocked. Other similar conditions can be shown and are given by

$$C = \rho^2 \tau \quad (10)$$

Fig. 1. Resonator circuit diagram showing the two modes of cavity.



power is that if  $n_0 > n$ , then it is possible for the absorbed power to become negative. This means that power will be delivered by the atoms in the field. The fact that  $k > 0$  is referred to as population inversion and can be achieved in different ways.

Independent of the mechanism by which inversion occurs there are observed many variations on what Eq. (4) generally is for these situations. A few of the more important ones will be derived here. The calculations are straightforward, but certain conventions and notations which have been used lead to obscure the logical development.

### C. Transformation Line Terminated by Capacity

Transmission has terminated by the impedance given in Eq. (11) will have a voltage reflection coefficient given by

$$Z = \frac{V_0}{V} \quad (11)$$

where  $Z_0$  is the characteristic impedance of the line. Then, using Eq. (11) and assuming symmetry,

$$V = V_0 e^{-jZ_0 Z} \quad (12)$$

where  $V$  is the voltage at the input of the resonator. For the steady state sinusoidal case, let

$$V = V_0 e^{j\omega t} \quad (13)$$

where  $V_0$  is the amplitude of the voltage. Then the input impedance is given by

$$Z = \frac{V}{V_0} \quad (14)$$

It is seen from Eq. (14) that  $Z$  can be larger than unity if  $V_0$  is negative. If  $V_0 > 1$ , then the magnitude of  $Z$  is larger than the incident voltage and transmission is blocked. Other similar conditions can be shown and are given by

$$C = \rho^2 \tau \quad (15)$$

Fig. 1. Resonator circuit diagram showing the two modes of cavity.

**B. Product of Voltage Gain and Bandwidth**

An accepted form of merit for a cavity mixer is the product of  $G_m$  and bandwidth between half-power points. This can be derived by working out the general frequency dependent expression for  $v_o / G_m$ . An easier way is to use the definition for  $Q_m$

$$Q_m = \frac{1}{\Delta f} \quad (18)$$

where  $\Delta f$  is the bandwidth and  $f_c$  the center frequency. Figure 1 also gives an expression for  $G_m$

$$G_m = \frac{1}{Q_m} \quad (19)$$

This result shows that for a given mixer it is possible to compromise between gain and bandwidth.

**IV. NOISE IN AMPLIFIERS**

A cavity mixer connected directly to a transmission line will not be a very satisfactory amplifier. In the first place the load and source cannot be separated very effectively and result in an unstable system. The second and more important reason is that the thermal noise generated by the load would be amplified along with the input signal and pose the further circulation problem as shown in Fig. 2 to circumvent these difficulties. The circromagnetic nonreciprocal device permits signals to propagate easily in one direction (typically 0.1 to 2.0 db loss between ports) while attenuating (typically 20-50 db) signals propagating

in the other direction. Under matched conditions, it is seen that

the noise generated by the load  $R_L$  will be dissipated in the generator impedance  $R_s$ . The major source of noise is now the signal source itself.

A measure of the performance of an amplifier is its noise figure  $F$ , which is defined as the input signal-to-noise ratio divided by the output signal-to-noise ratio, i.e.,

$$F = \frac{N_o}{N_o + N_s} \quad (20)$$

Since  $N_s = G_m N_o$ , it follows that

$$F = \frac{1}{1 + G_m} \quad (21)$$

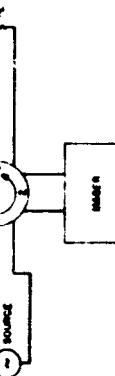


Fig. 2. Cavity-type mixer using a three-port circulator

Combining Eqs. (17), (18), and (19), gives

$$\Delta f G_m = \frac{\sum_i \Delta f_i}{Q_m Q_s} \quad (22)$$

It is seen from Eq. (17) that for high gain it is required that

$$Q_m \sim 1 \quad (23)$$

Thus, for the high-gain condition

$$\Delta f G_m \sim 2 \cdot Q_s \quad (24)$$

This result shows that for a given mixer it is possible to compromise between gain and bandwidth.

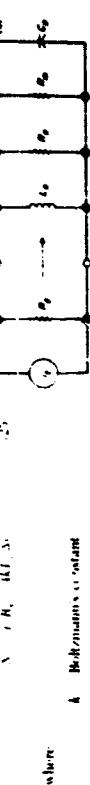


Fig. 3. Equivalent circuits for cavity mixer

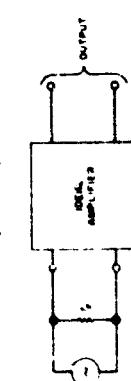


Fig. 4. Significance of system noise temperature  $T$

where  $\bar{I}_o^2$  is the mean squared noise voltage due to all internal noise sources. From Fig. 3b, it is seen that

$$\bar{I}_o^2 = \frac{N_o}{R_s} \cdot \frac{1}{R_s} \cdot R_s \quad (25)$$

where  $\bar{I}_o^2$  is the mean squared current due to all internal sources of noise, and  $R_s$  is the equivalent resistance of all the resistors in parallel (losses in the isolation used in this section).

$$\bar{I}_o^2 = \frac{N_o}{R_s} \cdot \frac{4 k T_s}{R_s} \cdot \frac{4 k T_s}{R_s} \cdot R_s \quad (26)$$

Finally, using Eq. (17), and assuming high currents ( $I_o$  the noise figure is found to be

$$F = \sqrt{N_o} \sim \sqrt{\frac{4 k T_s}{R_s}} \quad (27)$$

The second term is small compared with the third therefore

$$F \sim \sqrt{\frac{T_s}{R_s}} \quad (28)$$

Eq. (28) is much written in the form

$$F = \sqrt{\frac{T_s}{T_s + T_o}} \quad (29)$$

where  $T_o$  is the system noise temperature. The significance of  $T_o$  is seen in terms of the pick-up amplifier of Fig. 4. Assume connected to the output of Fig. 4 is a full bridge power meter, where  $f$  is the receiver's target noise temperature. It is noted that the receiver noise temperature may be integrated in the input circuit of the meter (in the sample transducer). Thus

$$T_o = T_s + T_f \quad (30)$$

Finally, it is necessary to remember the noise due to receiver losses in the transmission line. This noise contribution is again represented as a noise generator at temperature  $T$  in the mixer input circuit, as shown in Fig. 5. The temperature is given by Neumann (Ref. 19) as

$$T = \frac{1}{2} \left( T_s + T_o \right) \quad (31)$$

Finally, it is necessary to remember the noise due to receiver losses in the transmission line. This noise contribution is again represented as a noise generator at temperature  $T$  in the mixer input circuit, as shown in Fig. 5. The temperature is given by Neumann (Ref. 19) as

$$T = \frac{1}{2} \left( T_s + T_o \right) \quad (31)$$

where  
 $\alpha$  total attenuation in db

#### T. Transistor-diamond temperature

In practice  $T_c$  is taken to be 290 K (room temperature).

Equation (3) is a good approximation for low losses, i.e., the signal attenuation is negligible.

The expression for noise temperature of the receiving system is given by combining Eqs. (1), (2), and (3):

$$T_n \approx 700 \cdot T_e \cdot T_c \cdot T_g \text{ K}$$

## V. THREE-LEVEL PARAMAGNETIC MASERS

The discussions in the preceding sections were confined to generalities without reference to any specific mechanism by which microwave amplification might be achieved. In essence what is needed is a scheme in which atoms in an excited state may be placed in a microwave cavity which is tuned to the same frequency as that of the atomic resonance given by Eq. (1). In the ammonia maser, a beam of molecules was passed through an inhomogeneous electric field which sorted the excited molecules from the unexcited ones to provide laser action. A more versatile amplifier is the three-level spin maser which will now be described in some detail.

In addition to charge and mass, the electron appears to have an inherent spin angular momentum which, in turn, leads to a magnetic moment. If in some manner it is possible to suppress the most salient property of the electron, i.e., its electrical charge, then it is possible to consider the electron as a paramagnet. Such is the situation in which some of the electrons find themselves in the paramagnetic state, Fe, Fe<sub>2</sub>, Cr, Ni, etc. These ions exist in stable charge-neutralized states in compounds such as Cr<sub>2</sub>O<sub>3</sub>, but what are needed are the equivalents of isolated ions. This condition may be realized by making a small amount of Cr<sub>2</sub>O<sub>3</sub> with Al<sub>2</sub>O<sub>3</sub> and growing a doped sapphire crystal or ruby. Then it is seen that Cr ions may be dispersed fairly uniformly throughout the crystal. Those ions have an unoccupied filled lower electron shell in which three electrons may generate to yield a 40% range of relative strength three as compared with

a single electron. In quantum mechanical language, the electron is referred to as a spin 1/2 system thus, chromium doped sapphire is a spin 1/2 system. Moreover, one pair of electronic spins could be isolated itself so that a spin system also includes a spin 1/2 system.

The energy of a magnetic dipole of moment  $m$  is proportional to the field  $H$  in which the dipole is located:

$$W = mH$$

Equation (35) is plotted in Fig. 6 for an isolated spin system in which the paramagnetic ions are not isolated and are perturbed by the internal crystalline field. The resultant field, seen by the paramagnetic ion may be regarded as the vector sum of the externally applied field and the field due to the crystalline environment. The anisotropic character of the crystalline field leads to additional terms in Eq. (35) which are functions of the angular orientation of the crystal relative to the external field. Figure 7 shows the energy plotted as a function of applied field for the particular case of the C axis (optical axis) oriented 90 deg to the applied field (Ref. 12).

For a fixed magnetic field  $H$ , a new diagram can be drawn in which the number of ions in each energy state is kept fixed and the number of levels in each energy state is kept fixed. This is an approximate, atom switch, (see discussion in Ref. 11, Table IV, Chase and Sorenson of Handbook of tables of Ref. 12).

Equation (33) is a good approximation for low losses, i.e., the signal attenuation is negligible.

The expression for noise temperature of the receiving system is given by combining Eqs. (1), (2), and (3):

$$T_n \approx 700 \cdot T_e \cdot T_c \cdot T_g \text{ K}$$

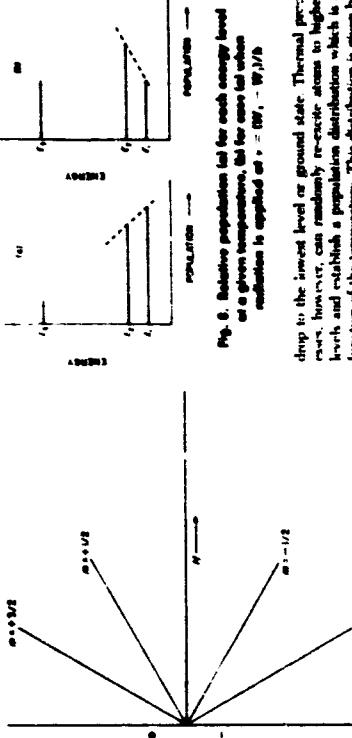


Fig. 6. Energy level diagram for isolated spin in magnetic field

where

$$\frac{n}{n_0} = e^{-\epsilon_i/kT}$$

$n$  is the number of ions in the energy level  $E_i$ ,  
 $n_0$  is the Boltzmann constant  
 $T$  is the absolute temperature

It is noted from Eq. (36) that the populations of two levels may be equilibrated by increasing the temperature. However, the application of heat in the usual way will not immediately lead to equilibration of all states. It was Bloemberger's (Ref. 2) observation that one has effectively "heat" a particular pair of levels by applying a resonance radiation appropriate to those levels. Thus, the population distribution curve shown in Fig. 8 is the curve of radiation applied at  $\lambda = 1.06 \mu$ . Note that now  $n_1 > n_0$ , in fact, in some of the distributions shown, it is as though the temperature were negative. Clearly, the energies of resonance have refer to a particular degree of freedom, and the term "heat temperature" has been generally adopted for this. It is to prove one of these ideas, in addition to the construction of a maser, it is necessary to determine enough information about a resonance curve for heat to another one source. The process is straightforward when the levels are degenerate in such a way that the radiation field does not provide the one for saturation as well as energy balance. There

is shown in Fig. 8a. It is a fundamental law of nature that, just as thermal dissipation, all the losses would

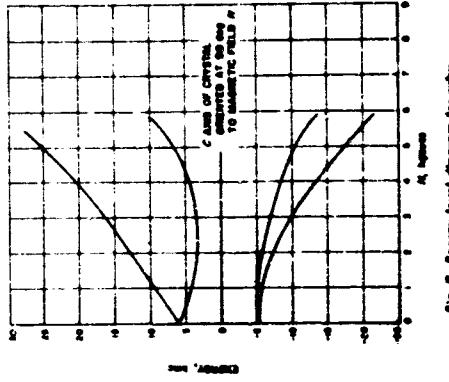


Fig. 7. Energy level diagram for ruby

be shown in Fig. 8a. It is a fundamental law of nature that, just as thermal dissipation, all the losses would

unenhanced level transitions the conservation of angular momentum results in, through the cooperative action of the crystalline field. It is this phenomenon which makes possible the solid-state maser.

The requirements for a solid-state maser have now been discussed and it remains to consider some of the alternative problems encountered in practical applications. The first requirement for an amplifier is a resonant cavity filled with rubidium and tuned to the signal frequency. Next, it is necessary to have the same cavity resonant at a higher mode at the pump frequency. The cavity is placed in a cleaver filled with liquid helium and the rubidium then heated to about 10°K. A klystron supplies the pump power and a circulator (Fig. 9) separates the output and input signals. Clearly there are many variations to the basic configuration and, in fact, there have been virtually as many different designs as there were masers built.

power is reflected back to the ruby because the strip-line circulator appears as a sharp discontinuity at the pump frequency.

Although various mechanical arrangements are possible to provide great flexibility in regard to tunability and coupling adjustments, it is generally found that the most stable configuration is one in which all parameters are fixed. The most serious problem associated with a cavity maser is that of gain stability as the ambient pressure and no pressurization should be overlooked.

An advantage of the cylindrical symmetry in the coaxial maser is that the C axis of the ruby is easily adjusted to be at right angles to the applied magnetic field. If the energy level diagram for this maseration was shown in Fig. 7 because the transition probabilities are particularly good here for a low frequency maser. The 1/2 levels are used for the signal transition and 1/3 levels for the pump transition. The usual practice is to number the levels in ascending order, starting with the lowest level as 1. The fourth level is not used here.

It is well to conclude this discussion by presenting our some of the more important aspects in the optimum design of masers.

The term "filling factor" has been generally adopted to indicate what fraction of a cavity has been filled with rubidium. The effective (removable) filling factor is also less than the geometrical filling factor because (a) the pumping RF field does not affect all parts of the ruby equally, and (b) the transition probability for the magnetic spin is a function of the orientation of the crystalline axes relative to the RF magnetic field. The dependence of transition probability on crystalline orientation is in general a complicated function, but the following rules are found to be very helpful: (1) For adjacent levels in a signal transition the RF magnetic field should be at right angles to the applied (constant) field,  $H_0$ . (2) For nonadjacent levels, i.e., a pump transition) the RF magnetic field should be parallel to the applied field,  $H_0$ .

Fig. 9. Basic requirements for a cavity-type maser

A fairly successful cavity-type maser has been built at JPL for L. and S. Stanch (Figs. 10 and 11). A quartz-wave crystal cavity is filled with ruby and is capacitively coupled to a coaxial transmission line. The signal is propagated in the TE<sub>11</sub> (circular) mode, while the pump propagates down the same coaxial line in the TE<sub>11</sub> (waveguide) mode. The use of the waveguide mode serves to keep the pump power out of the circulator, most of

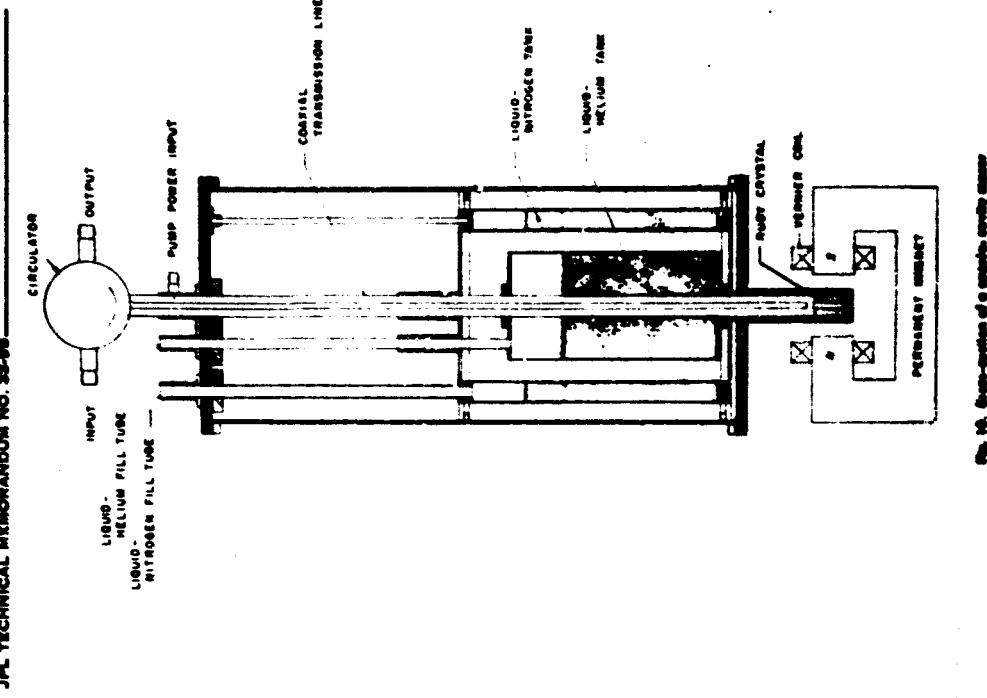
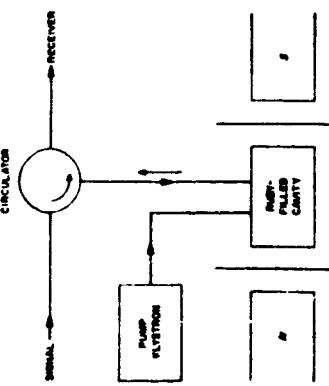


Fig. 8. Schematic of a ruby maser

$$\Omega_0 = \frac{2\pi H_0}{\lambda} \text{ (for a single mode)}$$

(17)



Quantitatively, it is seen from Eq. (12) that a few magnetic fields are desired. The quantity  $\Omega_0$  is defined in the usual way as

$$\Omega_0 = \frac{\text{total stored energy}}{\text{decrease (or increase) of energy per second}}$$

(17)

where  $H(x, z)$  is the magnetic field at each point in the cavity and  $P_{out}(x)$  is the power emitted by each element of volume of the paramagnetic crystal as given by Eq. (6) usually done on an integral basis.

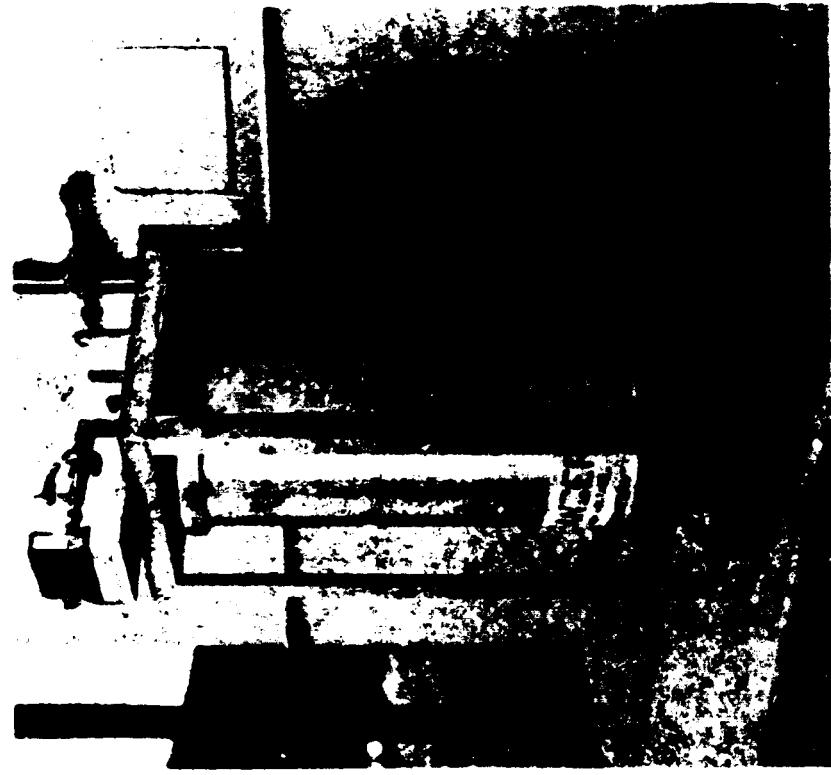


Fig. 11. Cavity maser assembly for localization measurements

## VI. MASER SYSTEMS—INSTRUMENTATION

An important part of a maser system is the instrument which permits monitoring of the gain and noise temperature of the maser. The need to monitor noise temperature is illustrated by a realistic example. It is possible to have a faulty connection in the crystal signal transmission line which could result in alternate by a few tenths of a dB the gain of the maser is reduced adjusted to compensate for this but the noise temperature of the maser is increased by approximately 7 deg for each tenth of a dB attenuation. This can be a large degradation of system performance.

In linear systems the noise powers due to different sources are additive and this greatly simplifies measurement procedure. There are two popular methods for measuring noise figures. First, a substitution method is employed as shown in Fig. 12. Here the input to the maser is connected alternately to two resistors kept at different temperatures and the output powers are compared. The ratio of the two powers yields

$$R = \frac{P_1}{P_2} = \frac{T_1}{T_2}$$

where  $T_1$  is the unknown total system temperature (Recall from Eq. 27 that noise power is proportional to temperature). Secondly, a fractional coupler may be employed with a noise diode (Fig. 13) to achieve the same result. When the noise diode is fixed, a noise power proportional to  $T_s$  is injected into the system and a comparison is made with the unmodified case. However

$$R = \frac{P_1}{P_2} = \frac{T_1 + T_s}{T_2}$$

Finally, a combination scheme may be used as shown in Fig. 14 when there are two resistors in a system that the antenna temperature  $T_a$  and also  $T_s$ , are to be determined. Power ratios are determined for the resistors in the two passive branches. These ratios are converted to the relations for  $T_a$  and  $T_s$ .



Fig. 12. Substitution method for noise figure measurements

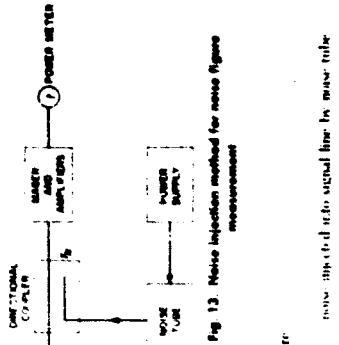


Fig. 13. Noise injection method for noise figure measurements

Because generally  $T_s < T_a$ ,  $T_s$  can often be neglected.

The second method is much preferred for use with cavity masers because the first method suffers from the serious difficulty of gain changes in the input as well as output. Gain variations in the noisy cavity system make temperature to vary continually by changing the noise contribution from the feedback loop (see Fig. 3).

Finally, a combination scheme may be used as shown in Fig. 14 when there are two resistors in a system that the antenna temperature  $T_a$  and also  $T_s$ , are to be determined. Power ratios are determined for the resistors in the two passive branches. These ratios are converted to the relations for  $T_a$  and  $T_s$ .

The sum of a noise is readily determined by injecting a selected buffer and after the mixer. The control conditions for a noise source are shown in Fig. 15. Only one of the wave tanks is necessary to operate the source, while all the other tanks are required for maintaining gains having width, center temperature, etc.

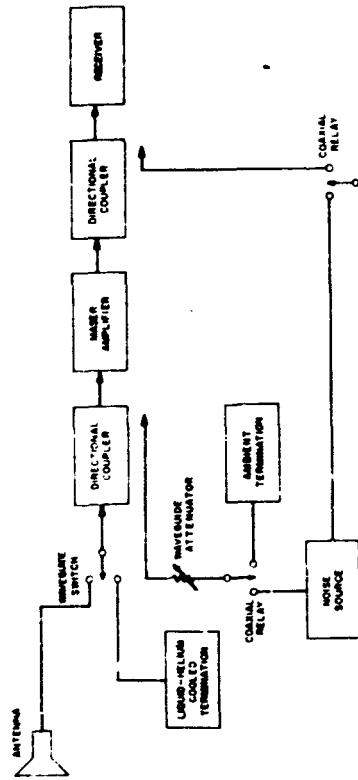


Fig. 14. Method for measuring antenna noise temperature, noise noise temperature, and noise gain.



Fig. 15. Control console for a maser system.

## VII. CRYOCOOLERS

A very elementary part of a maser is the cooler system which sends the radio drive to liquid helium temperatures (4.2 K or less). A cross-section of the JPL maser is shown in Fig. 10.

Aside from the outer housing made of aluminum, most of the major parts were made of stainless steel. The unit was demountable, being sealed with Neoprene O-rings. A titanium ion pump was used to maintain a vacuum in spite of the inevitable slow leak of helium into the chamber.

When the unit was used at the site of an 85-ft antenna, 3 liters of helium and 7 liters of nitrogen were required for an operational life of 20-30 hr. The stainless steel parts were welded or silver soldered. Although features of the dewar are well-splashed, it may be worthwhile to state that the rate of consumption of liquid helium is greatly affected by the way in which helium vapor is allowed to escape from the vessel. Ideally, the gas should have panel contact with the coaxial line in order to extract heat as it rises. Figure 16 shows the after-mast maser being filled with liquid helium.

More recently JPL has used a Cavitron antenna system as shown in Fig. 17. The maser is installed in the tower as in Fig. 18. (The Cavitron antenna has been chosen for its operational frequency of 6.6 Mc and its shown improved overall noise performance over the open mounted feed system. A minimum noise temperature of around 46° K was achieved, whereas the previous minimum was around 55° K.)

The inconvenience of having to refill a dewar is quite obvious, and much effort is being expended by various manufacturers to perfect a closed-cycle refrigeration (CCR) system for maser applications. A commercially available CCR system is shown in Fig. 19. Figure 20 shows the compression unit which supplies helium to the refrigerator unit through three small-diameter pipes. This type of CCR was developed originally for Bell Telephone Laboratories by Kelvin 12 Limited. The antenna-mounted maser uses very successful and sturdy CCR's as now being marketed for a traveling-wave maser.



Fig. 17. An open-mounted antenna and liquid helium.



Fig. 18. An open-mounted antenna and liquid helium.

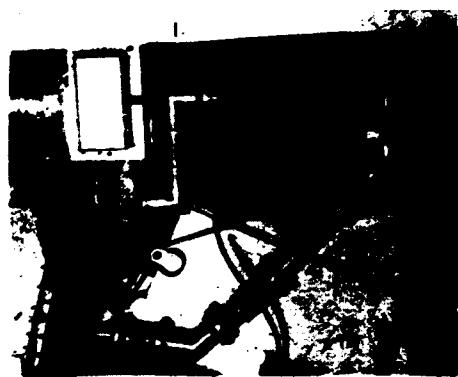


Fig. 18. Motor mounted in Cassegrain cone.

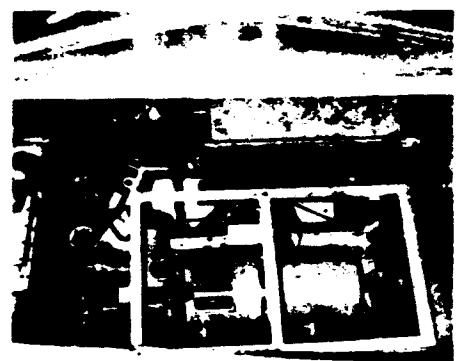


Fig. 19. Motor in dead-cycle refrigerator mounted in Cassegrain cone for tests.

### VIII. TRAVELING-WAVE MASERS

In its simplest form a traveling wave maser (TWM) consists of a waveguide filled with active paramagnetic material. The total gain of such an amplifier is, therefore, the gain per unit length multiplied by the total length. This means that the longer the interaction time between the electromagnetic field and the maser material the greater will be the gain. A cascaded set of cavity type masers may, indeed, be made to function at TWM. If isolators are used between each set of cavity type masers a unilateral amplifier results.

In the TWM developed at Bell Telephone Laboratories (Ref. 6), a set of quarter-wave posts formed a comb structure (Ref. 6).

ture for the signal. On one side of the comb structure was a piece of moly which provided the amplification. Ferrite material is periodically placed between adjacent posts at a region where the RF magnetic fields are both in space and time quadrature. The circular polarization of these planes has opposite sense for the forward and backward waves and the ferrite absorbs energy from one wave in the other. Hence, a unidirectional maser is achieved.

TWMs have greater gain and bandwidth capability than do cavity type masers and are much more stable. These are, of course, much more complicated than a cavity type maser.



Fig. 20. Compressor unit supplying propane bottom to CDR of Fig. 19.

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